Impact of Advanced Vehicle Technologies on Energy Consumption for the City of Detroit Using Transportation System Simulations

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Impact of Advanced Vehicle Technologies on Energy Consumption for the City of Detroit Using Transportation System Simulations

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***Abstract*—In developing a transportation system model, the energy impact of the model is extremely important for sustainability and validation. One approach to evaluating the energy impact is to consider the amount of fuel consumed by transportation in the model for different scenarios and technologies. Argonne National Laboratory has collaborated with the Southeast Michigan Council of Governments (SEMCOG) and the Detroit Department of Transportation to develop and validate a transportation system model for Southeast Michigan, focusing on the city of Detroit.**

The objective of this paper is to analyze the vehicle energy consumption in the Detroit Transportation System model. The focus is on evaluating the SEMCOG road network drive cycles as performed with current and future vehicle technologies.

I. Introduction

Understanding the energy consumption of current and future vehicle technologies under real-world conditions is critical to estimating the overall impact of system models. Estimating the energy consumption during measured real-world drive cycles provides a good approximation, but does not ensure a consistent impact on the transportation system model as a whole [1]. This is why it is important to evaluate the energy impact on the drive cycles generated by the system model itself.

The transportation system modeling tool Polaris [2] is used to develop and validate a transportation system model for Southeast Michigan. It utilizes population and vehicle synthesis, along with activity demand generation and traffic flow, to model the transportation system.

The resulting stochastic speed profiles from Polaris, combined with the data on drive cycles and fleet distribution, are used as inputs to Autonomie, a vehicle system modeling tool. Autonomie [3] then simulates the energy consumption of the transportation network for different vehicle technologies. Figure 1 illustrates the steps involved in the process.

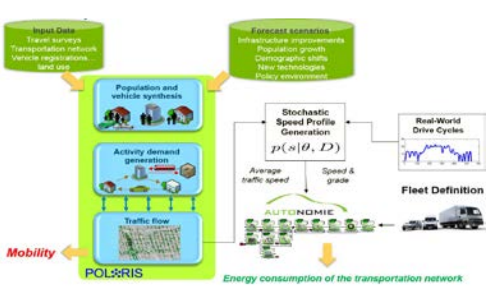

Fig. 1. Detroit Transportation Network Modeling Using Polaris and Autonomie

II. Polaris Detroit Model

The Southeast Michigan Council of Governments (SEMCOG) planning network [4] is used to model the Detroit road network that covers the entire Southeast Michigan Metropolitan Planning Organization (MPO) model area. Figure 2 illustrates a snapshot of the Detroit road network that has been developed.

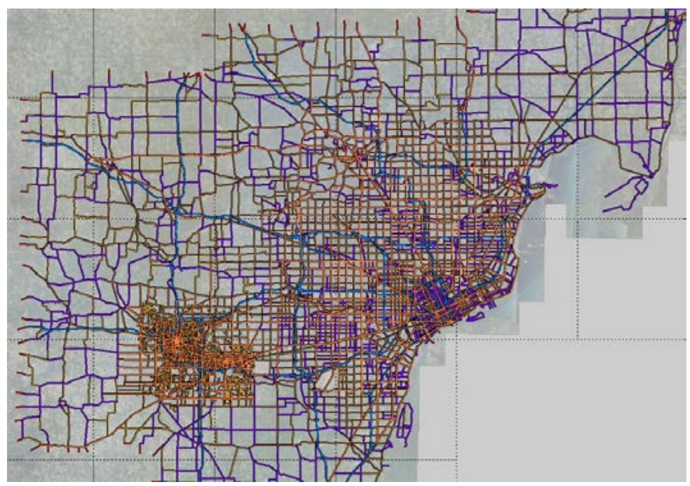

Fig. 2. Detroit Road Network (SEMCOG Case)

The distribution of population and employment in the area is developed using Census 2010 [5], American Community Survey [6], and SEMCOG data. This distribution is used as an input to Polaris to develop the model. Figure 3 illustrates the employment and population densities.

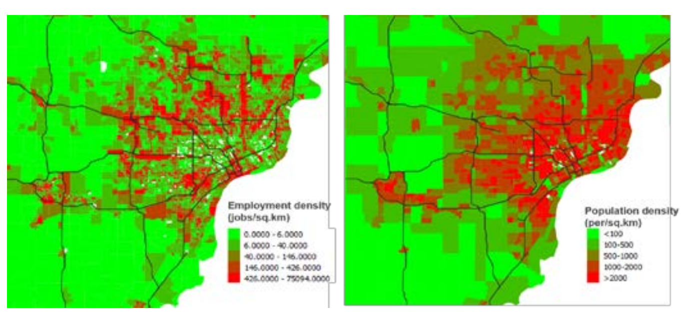

Fig. 3. Detroit Employment and Population Density

Vehicle fleets are distributed among the simulated households on the basis of current vehicle registration data obtained at the Zip Code level [7]. The vehicles are assigned to each agent in Polaris on the basis of household classifier characteristics. The transportation model generates traffic flows for each road link for different vehicles. These traffic flows are then used by a stochastic speed profile generation process to generate vehicle trip profiles for use in Autonomie. Figure 4 illustrates the distribution of the free-flow speed of the various links in the road network.

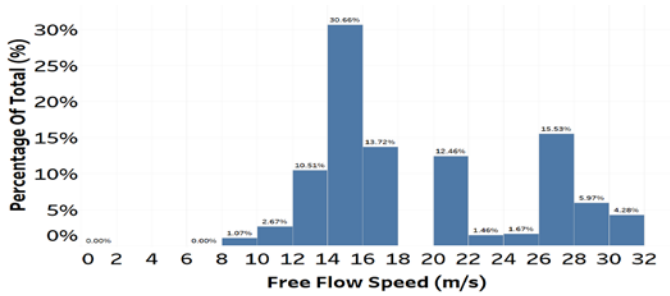

Fig. 4. Distribution of Free-flow Speed (m/s) for the Various Links

As an example, Figure 5 demonstrates a particular trip that includes 23 different road links and the free-flow speed of these links.

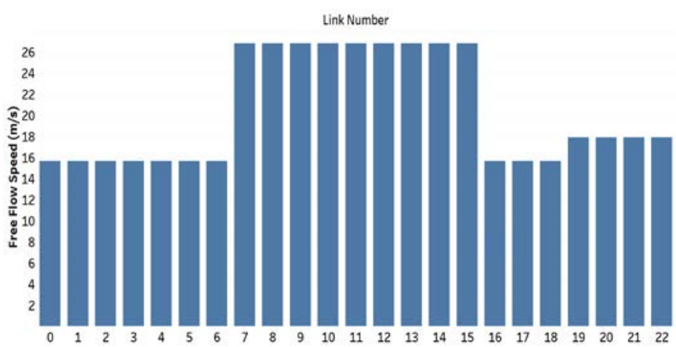

Fig. 5. Distribution of Free-flow Speed (m/s) for Trip # 100

After the stochastic speed profile generation, the vehicle trip profile is generated for the Autonomie format as seen in Figure 6.

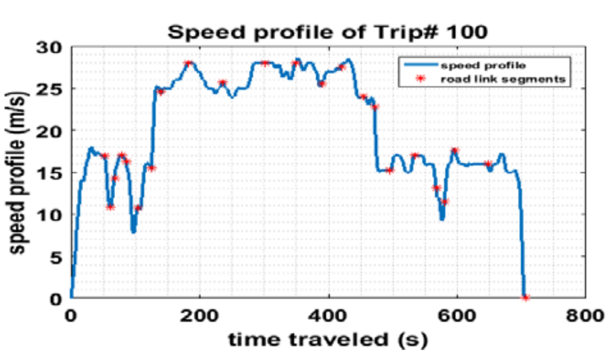

Fig. 6. Autonomie-format Speed Profile for Trip # 100

III. Autonomie

The vehicle system simulation tool Autonomie is used to perform simulations of drive cycles with vehicle models that incorporate baseline and advanced vehicle technology targets as generated for the U.S. Department of Energy [8] and the U.S. Department of Transportation [9]. The vehicle models used to evaluate the energy consumption on the simulated drive cycles consist of gasoline conventional powertrains, power-split HEVs, plug-in hybrids (PHEVs), fuel-cell hybrids (FCHEVs) and battery electric vehicles (BEVs). Multiple EPA class definitions of vehicles (Compact, Midsize, Midsize SUV and Midsize Truck) have also been used to evaluate the energy consumption of the driving profiles [10]. Market penetration models are used to select the advanced vehicle powertrain models for future years.

Table I details a subset of the different vehicle powertrains used to represent the fleets for two different time frames:

TABLE I
Autonomie Vehicle Models Considered

Lab Year	**Powertrain**	**Vehicle Technology**	
		Engine	Transmission
	CONV	[DOHC/PFI/VVT]	6-AU
	Split HEV	Prius	
2010	PHEV 40 AER	Prius	
	Fuel Cell HEV		
	BEV200		
	CISG (Start-Stop)	SkyActiv	10-AU
	Split HEV	Prius	
2040	PHEV 50 AER	Prius	
	Fuel Cell HEV		
	BEV200		

The component and vehicle assumptions are derived from the U.S. Department of Energy Targets for the lab years considered. Table II lists the detailed component-level assumptions derived for the different time frames.

TABLE II
Vehicle Component Assumptions

Component Assumption	**Powertrain**	**Lab Year** 2010	2040
Battery Specific Power (W/kg)	HEV	2750	6000
	PHEV	450	1500
	FCHEV	659	870
	BEV	659	870
Battery Energy Density (Wh/kg)	PHEV	100	188.89
	BEV	190	340
Engine Efficiency (%)	CONV	34.80	38.78
	HEV	40	52
Motor Efficiency (%)	BEV	92	97

IV. Results & Analysis

A. *Baseline Vehicle Technologies (Lab Year 2010)*

The distribution of fuel consumption rate for the full set of simulations in Figure 7 illustrates the variance involved in simulating the drive cycles with the baseline vehicle technologies.

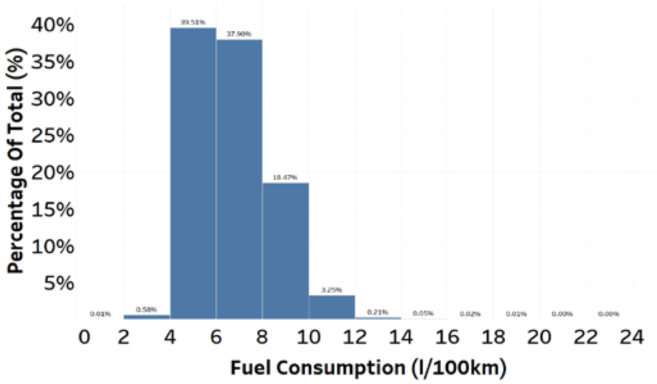

Fig. 7. Fuel Consumption Rate Distribution for Baseline Vehicle Technologies

Figure 8 shows the fuel consumption rate (l/100 km) as a function of trip distance (km) for the different vehicle classes considered. For simplicity, only the gasoline conventional powertrain is considered.

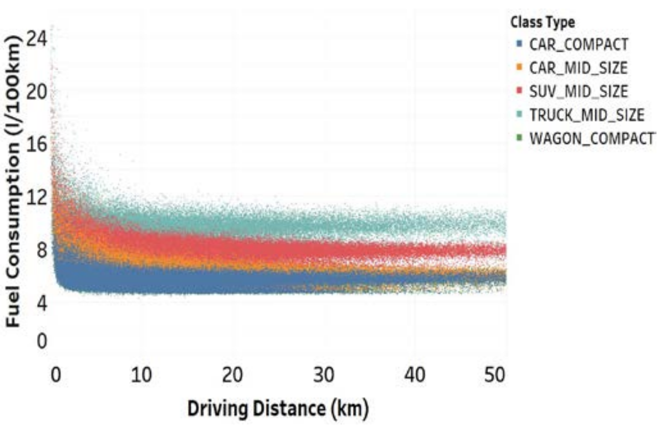

Fig. 8. Fuel Consumption Rate vs. Driving Distance for Conventional Powertrain

It can be observed that the fuel consumption rate of the compact car and compact wagon vehicle classes ranges from 5.12 l/100 km to about 6 l/100 km. The fuel consumption rate for the midsize car vehicle class blends with the compact results, but ranges from 6.7 to 8.33 l/100 km. For the midsize SUV vehicle class, the fuel consumption rate increases to about 7.41 to 8.55 l/100 km, while the fuel consumption rate for the midsize trucks (pickups) ranges from around 8.7 to 10.3 l/100 km across the driving distances examined.

The evolution in amount of fuel consumed (kg) across the trip distances (km) is illustrated in Figure 9 for the different vehicle classes. Again, for simplicity, only the gasoline conventional powertrain is considered.

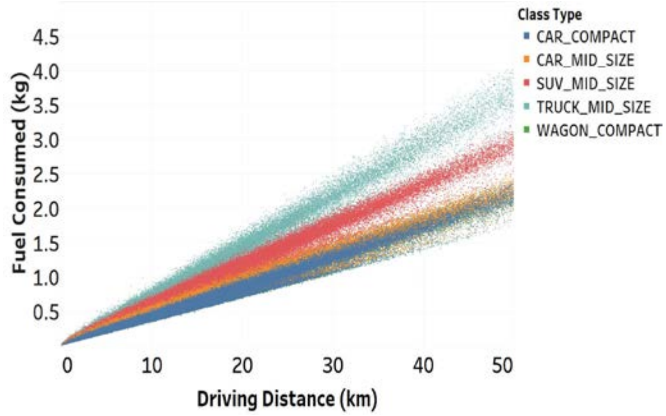

Fig. 9. Fuel Consumed vs. Driving Distance for Baseline Vehicle Technologies

It can be observed that the amount of fuel consumed is proportional to the driving distance. This relationship tends to differ across the different vehicle classes, with the gradient getting steeper as vehicle weight increases from compact car to midsize truck. At the 50-km driving distance mark, the amount of fuel consumed for compact cars ranges from 1.4 to 1.7 kg. The midsize-car results blend with the compact-car results, with a higher upper limit of 1.9 kg. The amount of fuel consumed by the midsize SUVs ranges from 2.3 to 2.7 kg, and the amount of fuel consumed by the midsize trucks ranges from 3.3 to 4.0 kg.

The evolution of the different powertrains in terms of fuel consumption rate (l/100km) and amount of fuel consumed (kg) is explained below. For simplicity and the distribution of drive cycles, all the results presented are for the compact-vehicle class.

The evolution of fuel consumption rate across the different powertrains is illustrated in Figure 10.

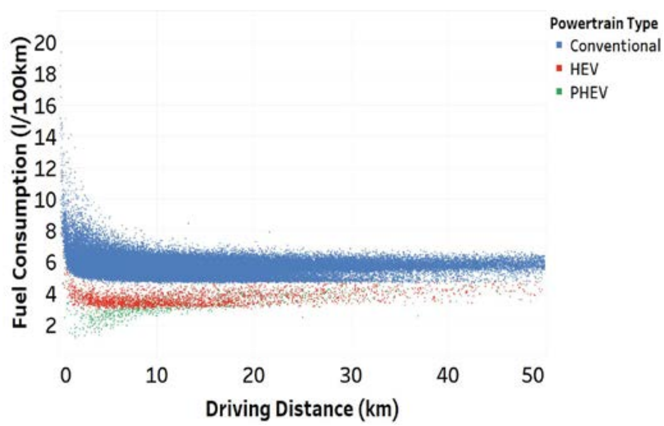

Fig. 10. Fuel Consumption Rate vs. Driving Distance Across Powertrains for Baseline Vehicle Technologies

Along with the previous observation of fuel consumption rate ranges for conventional vehicles (Figure 8), it can be observed that the power-split HEV fuel consumption rate ranges from 3.1 to 4.5 l/100 km, while the PHEV fuel consumption rate ranges from 1.3 to about 3.1 l/100 km.

The evolution of fuel consumed across the different powertrains is illustrated in Figure 11.

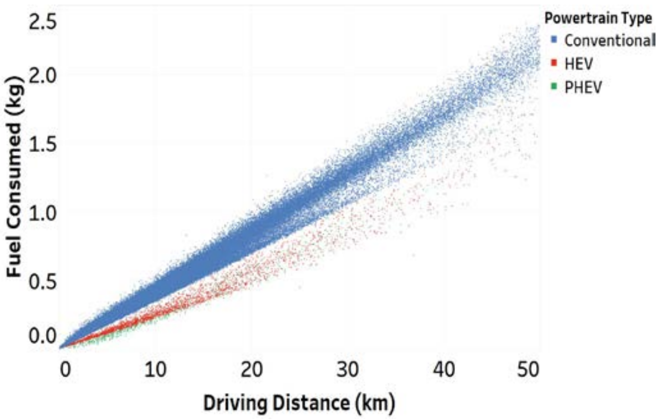

Fig. 11. Fuel Consumed vs. Driving Distance Across Powertrains

Along with the previous observation of the range in amount of fuel consumed by the gasoline conventional powertrain at the 50-km driving distance, it can be observed that the amount of fuel consumed by the power-split HEV ranges from 1.4 to 1.7 kg.

B. Future Vehicle Technologies (Lab Year 2040)

The impact of advanced technology targets for the different vehicle component assumptions can be evaluated in terms of fuel consumption improvements during the drive cycles. Figure 12 shows the distribution of fuel consumption rates for the full set of simulations.

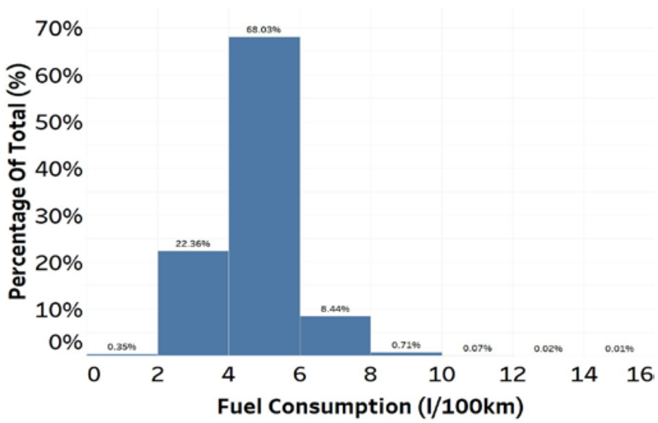

Fig. 12. Fuel Consumption Rate Distribution for Future Vehicle Technologies

Figure 13 illustrates the fuel consumption rate (l/100 km) as a function of trip distance (km) for the different vehicle classes considered. Again, for simplicity, only the gasoline conventional powertrain is considered.

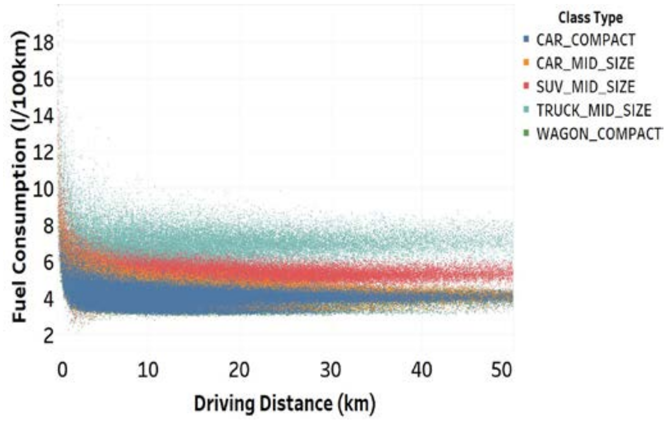

Fig. 13. Fuel Consumption Rate vs. Driving Distance for Future Vehicle Technologies

It can be observed that the overall fuel consumption rate across the different vehicle classes has significantly improved as a result of vehicle technology improvements. For compact and midsize cars, the fuel consumption rate ranges from 3.33 to 5.6 l/100 km. For midsize SUVs, the fuel consumption rate ranges from 5.56 to 6.7 l/100 km across the driving distances, while the fuel consumption rate for midsize trucks ranges from 7 to 10 l/100 km. The evolution in amount of fuel consumed (kg) across the trip distances (km) is illustrated in Figure 14 for the different vehicle classes. Again, for simplicity, only the gasoline conventional powertrain is considered.

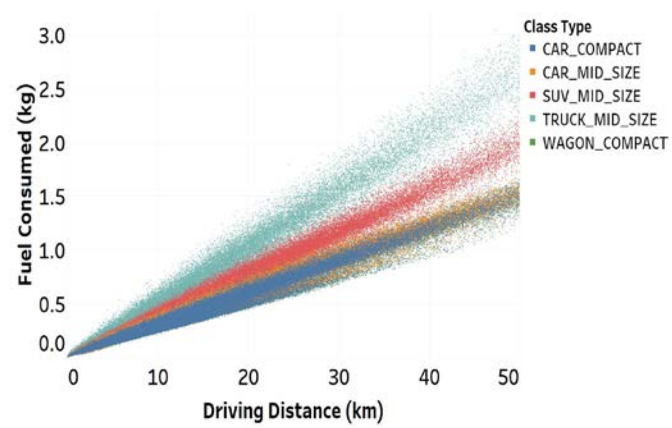

Fig. 14. Fuel Consumed vs. Driving Distance for Future Vehicle Technologies

The amount of fuel consumed follows a similar proportional relationship to that observed previously with respect to the different vehicle classes. The amount of fuel consumed by the compact and midsize cars ranges from 1 to 1.5 kg. The amount of fuel consumed by midsize SUVs ranges from 1.6 to 2.0 kg, while the amount of fuel consumed by midsize trucks ranges from 2.1 to 2.9 kg.

The evolution of the different powertrains in terms of fuel consumption rate (l/100 km) and amount of fuel consumed (kg) is explained below. For simplicity and the distribution of drive cycles, only compact vehicles are considered.

The evolution of fuel consumption rate (l/100 km) across the different powertrains is illustrated in Figure 15.

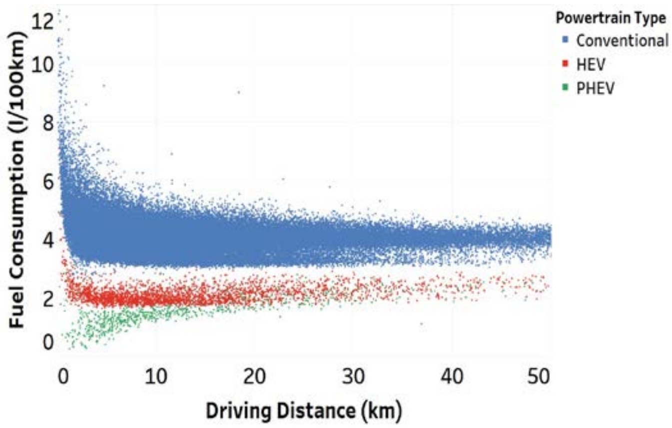

Fig. 15. Fuel Consumption Rate vs. Driving Distance Across Powertrains for Future Vehicle Technologies

It can be observed that the fuel consumption rate across multiple powertrains has also improved as a result of the advanced vehicle technologies.

The evolution in amount of fuel consumed across the different powertrains is illustrated in Figure 16.

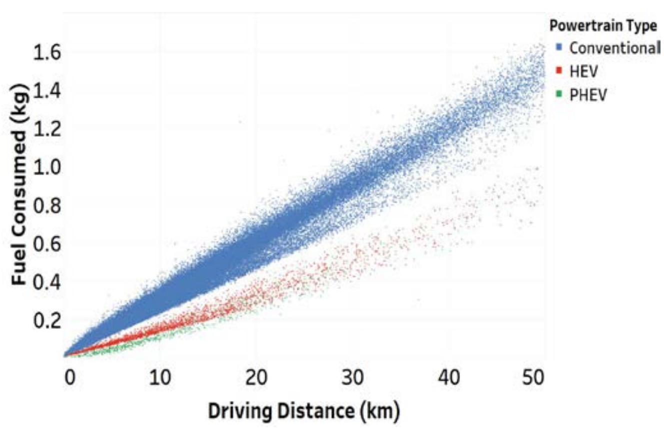

Fig. 16. Fuel Consumed vs. Driving Distance Across Powertrains for Future Vehicle Technologies

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V. Significance of the Difference

This section will focus on the likelihood that a difference between two samples (2010 vs. 2040 vehicles) is caused by something other than random chance. Given the large number of randomly assigned trips, it is crucial to approach the problem with an inferential statistical method [11]. The box plot in Figure 17 shows the variability within and between samples, with a larger variance for 2040 simulated vehicles. There appear to be some clear differences between the 2010 and 2040 simulated vehicles, but evaluating the difference in the variance between the two samples demands a more sophisticated and careful analysis. If we consider $X = X_1, X_2, \ldots, X_n$ to be a random sample of n fuel consumption numbers from 2010 vehicles assumed to follow a normal distribution with a mean μ_x and variance σ^2; and if $Y = Y_1, Y_2, \ldots, Y_m$ is an independent random sample of m fuel consumption numbers from 2040 vehicles assumed to follow a normal distribution with a mean μ_y and variance σ^2, then a natural estimate of μ_x - μ_y is $\widehat{\mu_x} - \widehat{\mu_y} = \hat{X} - \hat{Y}$, where $\hat{X}$ *and* $\hat{Y}$ are the sample means for the data vectors X and Y. $\hat{X} - \hat{Y}$ may be expressed as a linear combination of independently and normally distributed random variables

$$\hat{X} - \hat{Y} \sim N\left[\mu_x - \mu_y, \left(\frac{1}{n} + \frac{1}{m}\right)\sigma^2\right]$$

We therefore can account for a pooled sample variance ${s_p}^2$

$${s_p}^2 = \frac{(n-1){s_x}^2 + (m-1){s_y}^2}{m+n-2}$$

where ${s_x}^2 = \frac{1}{n-1}\sum_{i=1}^{n}\left(X_i - \hat{X}\right)^2$ and ${s_y}^2 = \frac{1}{m-1}\sum_{i=1}^{m}\left(Y_i - \hat{Y}\right)^2$

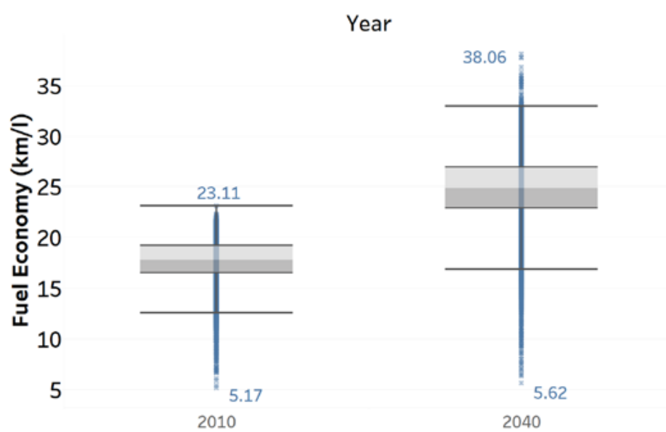

Fig. 17. Variance Analysis for Fuel Consumption Distribution

It can be shown that the statistic of interest T below follows a *t* distribution with *n* + *m* – *2* degrees of freedom:

$$T = \frac{\left(\hat{X} - \hat{Y}\right) - \left(\mu_x - \mu_y\right)}{s_p\sqrt{\frac{1}{n} + \frac{1}{m}}} \sim t_{n+m-2}$$

VI. Conclusion

The percentage improvement for advanced vehicles in fuel consumption rate and amount of fuel consumed across the different vehicle classes for conventional gasoline powertrains is shown in Figures 18 and 19, respectively.

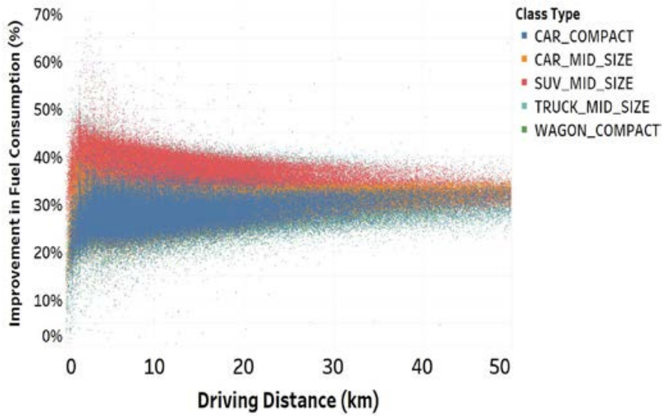

Fig. 18. % Improvement in Fuel Consumption Rate (l/100 km)

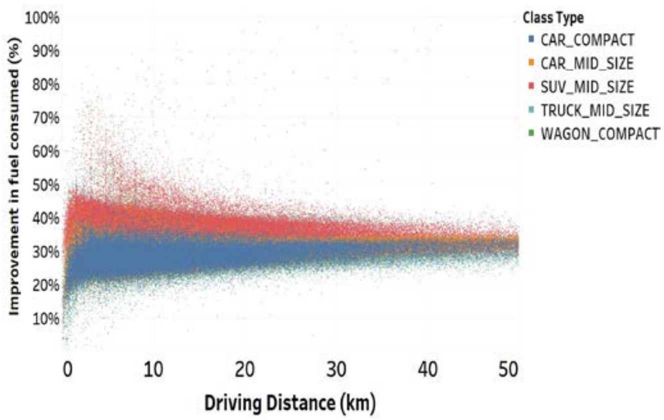

Fig. 19. % Improvement in Fuel Consumed (kg)

With the SEMCOG scenario case for the Detroit Transportation System model, the vehicle class ranking, in terms of the potential benefits of utilizing advanced vehicle technologies, is as follows: Midsize SUV > Midsize Car > Compact Car/Compact Wagon > Midsize Truck.

This paper presents a framework to integrate different transportation system simulation models and evaluate different parameters of interest. Further studies will be developed that evaluate emissions and cost impacts for the different technology assumptions, along with different scenarios for the Detroit model. This study could also be evolved to evaluate transportation system models for different cities.

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